Ultra High Density SiPMs for Challenging Radiation Environments

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Outline

- SiPM radiation damage
- SiPMs for the CMS HE Phase 1 Upgrade
- SiPM goals for the CMS HCAL Phase 2 Upgrade
- SiPM R&D for the CMS Phase 2 Upgrade
- Small cell size (5-12 um) FBK SiPMs
- Plans for future SiPM R&D

SiPM: radiation hardness

Radiation may cause:

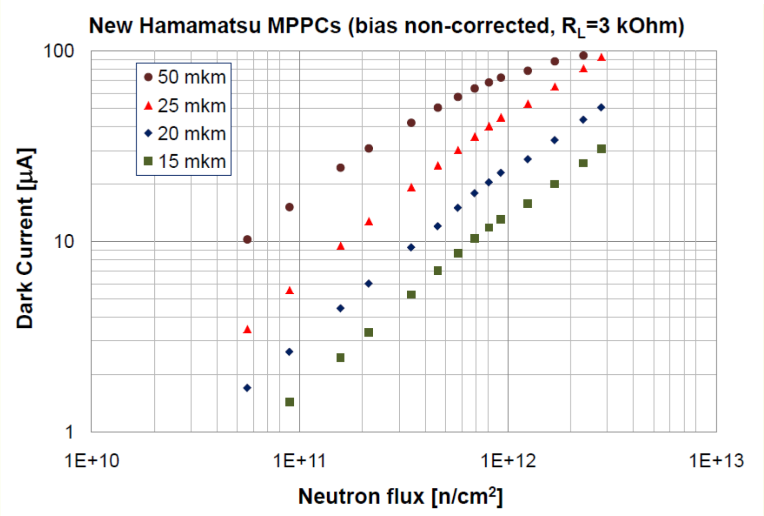
- Fatal SiPMs damage (SiPMs can't be used after certain absorbed dose)
- Dark current and dark count increase (silicon …)
- Change of the gain and PDE vs. voltage dependence (SiPMs blocking effects due to high electric field induced dark carriers generation-recombination rate)
- Breakdown voltage change

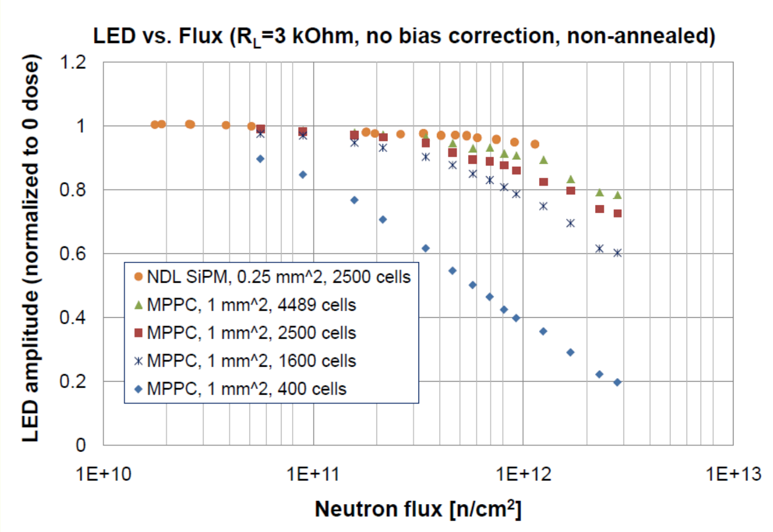
High energy neutrons/protons produce silicon defects which cause an increase in dark count and leakage current in SiPMs:

$$I_d \sim \alpha{*}\Phi{*}V{*}M{*}k,$$

α – dark current damage constant [A/cm];
Φ – particle flux [1/cm^2];
V – silicon active volume [cm^3]
M – SiPM gain
k – NIEL coefficient

α_{Si} ~$4{*}10^{-17}$ A*cm after 80 min annealing at T=60 C (measured at T=20 C)

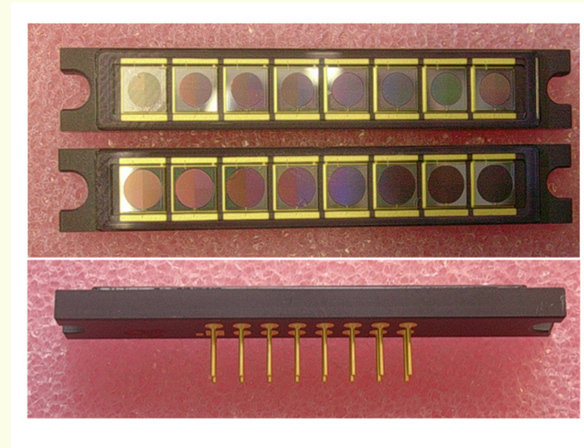


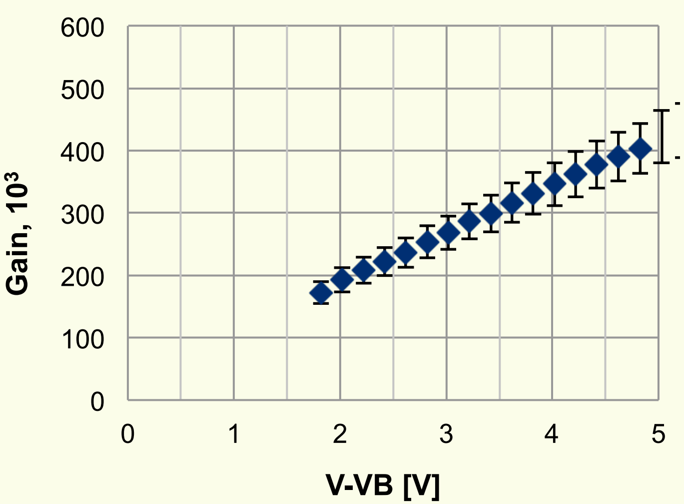


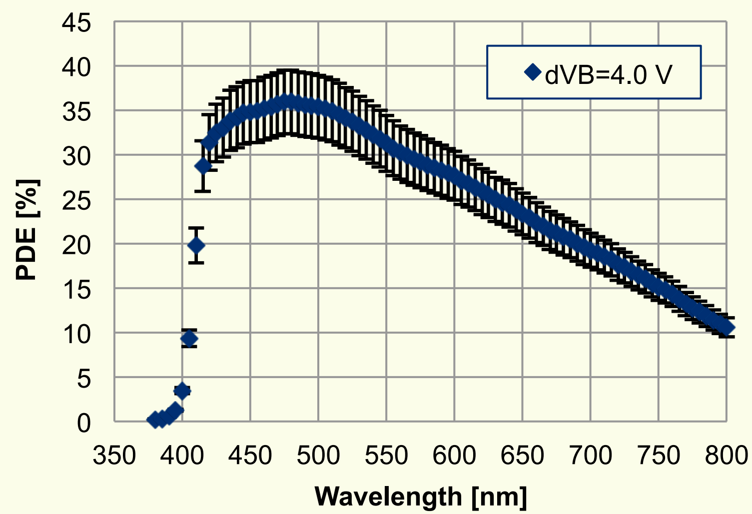
CMS HE SiPMs

SiPMs with large dynamic range were developed by CMS HCAL SiPM group in cooperation with Hamamatsu (Japan)

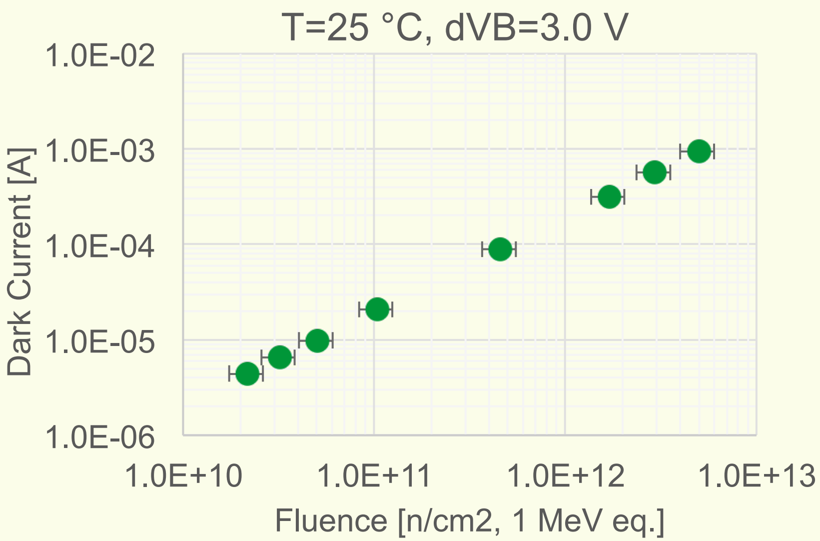
- Area: ~Ø2.8&3.3 mm
- Cell pitch: 15 um
- PDE(500 nm, dVB=4 V): 35%
- Gain (dVB=4.0 V): 330 000
- ENF(dVB=4.0): ~1.2
- Optical X-talk between cells: <20%
- Cell recovery time: ~7 ns

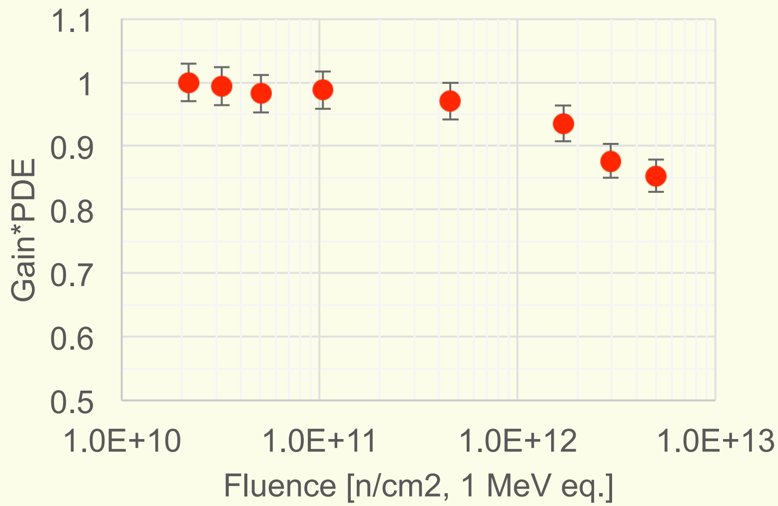






HE SiPMs after neutron irradiation





For CMS HE (3000 fb^{-1}): neutron fluence ~1E11 n/cm^2. SiPM dark current will reach ~20 uA, and signal drop will be <5%.
At 5E12 n/cm^2 the SiPM dark current reaches ~1 mA (dVB=3.0V) and Gain*PDE drop is ~15%. Most of he signal reduction comes from cell blocking and self-heating effects due to very high dark current.

Goals for the Phase 2 Upgrade

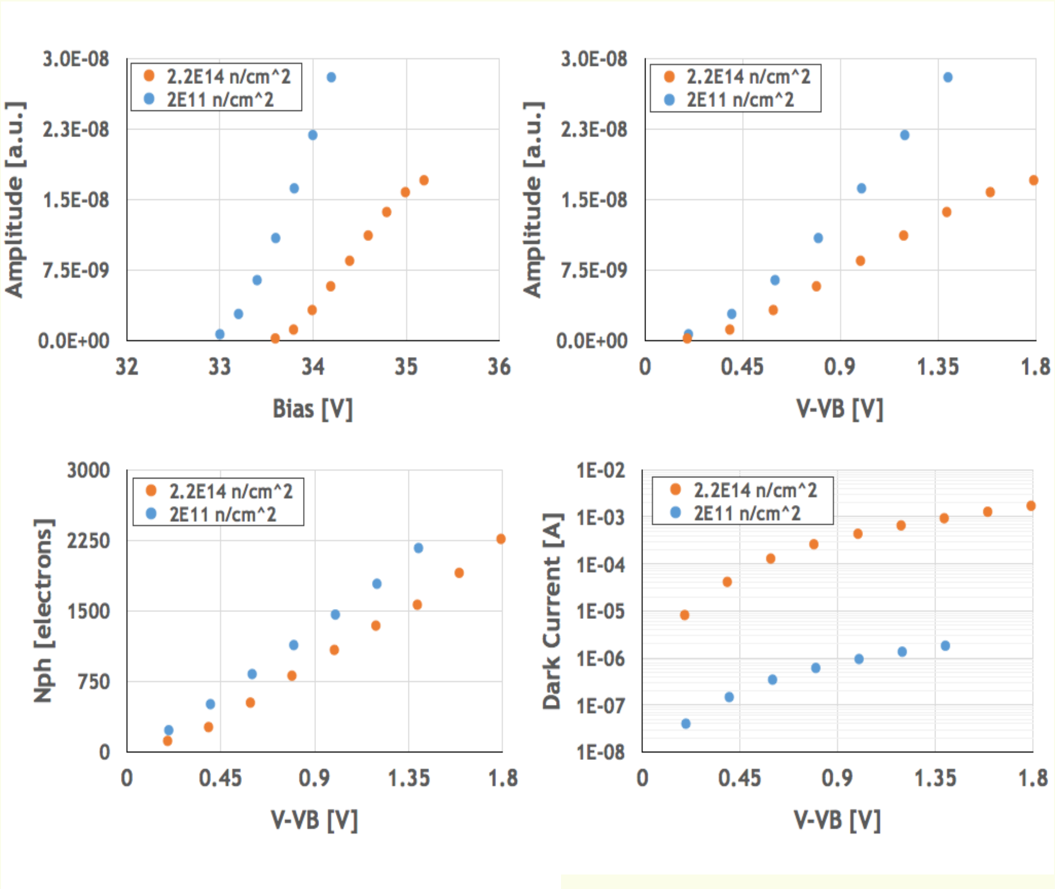
For the CMS Phase 2 Upgrade SiPMs should operate with high PDE~10%, low dark current (<100 uA/mm^2) and acceptable noise (to see MIP) after neutron fluence up to 1E15 n/cm^2.

Solution:

- Cell size reduction (5-7 um cell pitch)
- Small cell recovery time (<5 ns)
- Low (-30 °C) temperature operation

SiPM irradiated up to $2.2*10^{14}$ n /cm^2

First promising result: FBK SiPM (1 mm^2, 12 μm cell pitch was irradiated with 62 MeV protons up to $2.2*10^{14}$ n /cm^2 (1 MeV equivalent).



We found:

- Increase of VB: ~0.5 V
- Drop of the amplitude (~2 times)
- Reduction of PDE (from 10% to 7.5 %)
- Increase of the current (up to ~1mA at dVB=1.5 V
- ENC(50 ns gate, dVB=1.5V)~75 e, rms

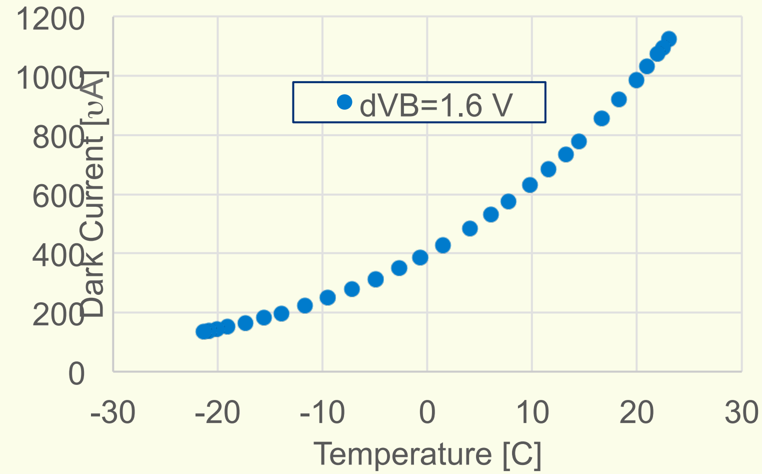
The main result is that SiPM survived this dose of irradiation and can be used as photon detector!

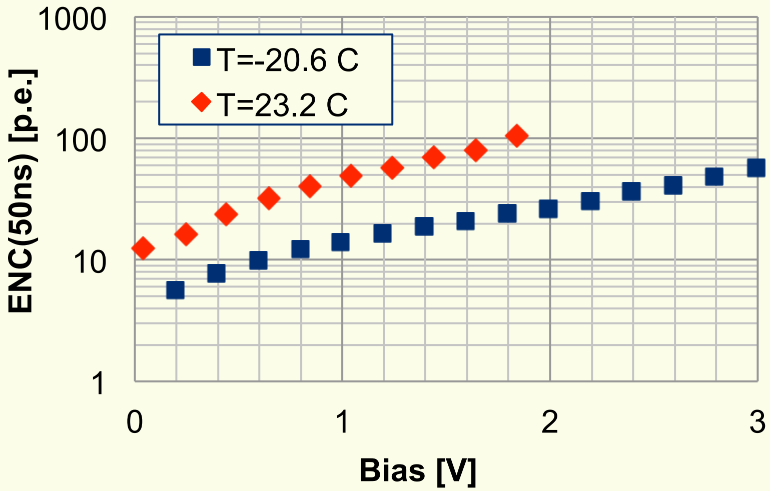
(A.Heering et al., NIM A824 (2016) 111)

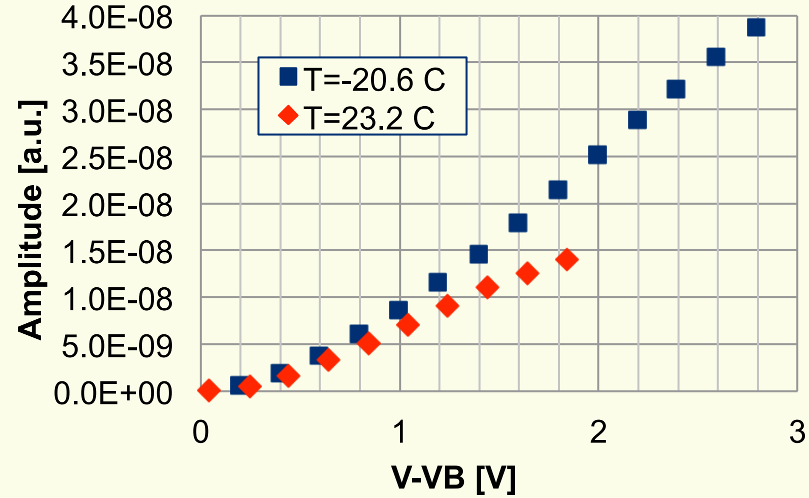
Irradiated SiPM at low T=-20.6 °C

<u>FBK 12 micron SiPM after 2.2E14 n/cm² at T=-20.6 °C:</u>

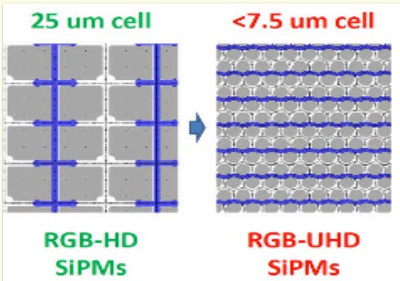
- A factor of ~9 drop of the dark current
- Reduction of noise: ~3 times
- Signal response partially recovers

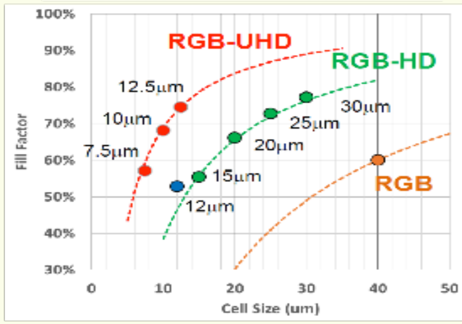






Joint effort with FBK on UHD technology





RGB-HD

cell size (μm)	cells/mm²
12	7000
15	4500
20	2500
25	1600
30	1100

RGB-UHD

cell size (μm)	cells/mm²
7.5	20530
10	11550
12	7400

FBK UHD Technology

Reduction of all the feature sizes

- Contacts
- Resistor
- …

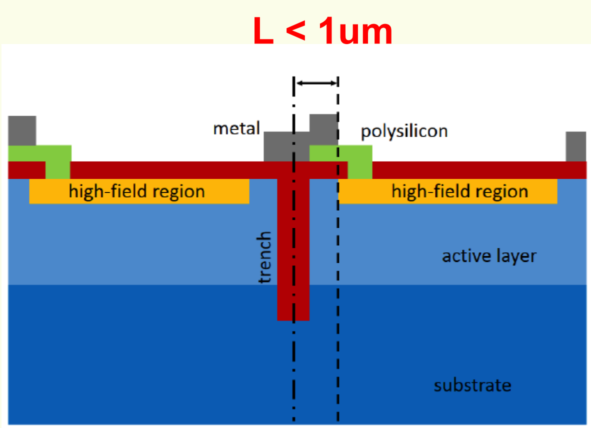
Reduction of the active-to-border distance (L)

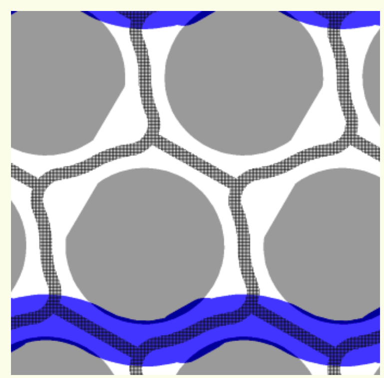
Circular active area (smaller cells)

- No corners (with lower field)
- Hexagonal cells arranged in honeycomb configuration

Lower R_q

- For even faster recharge

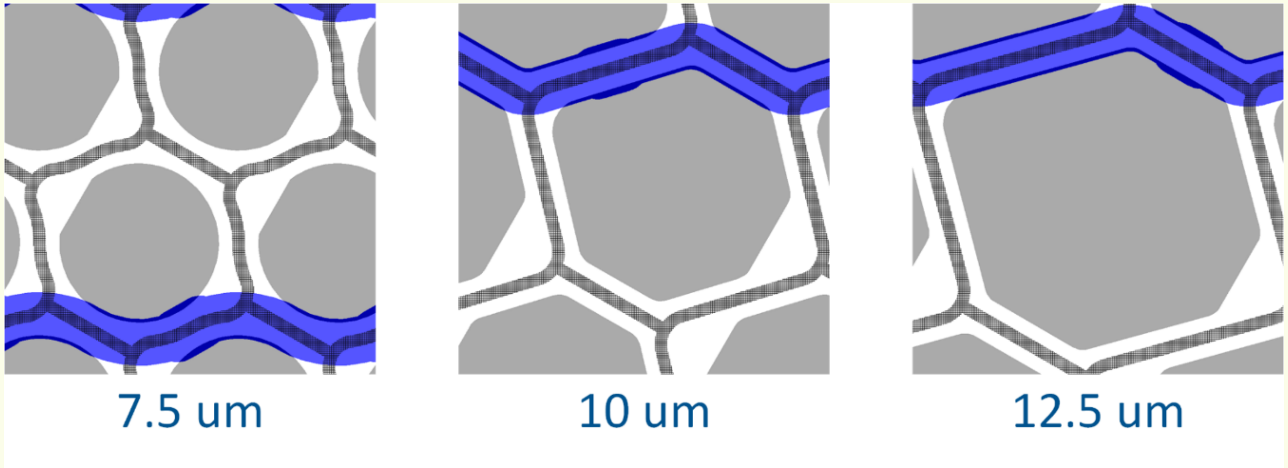




Different layouts for best GF

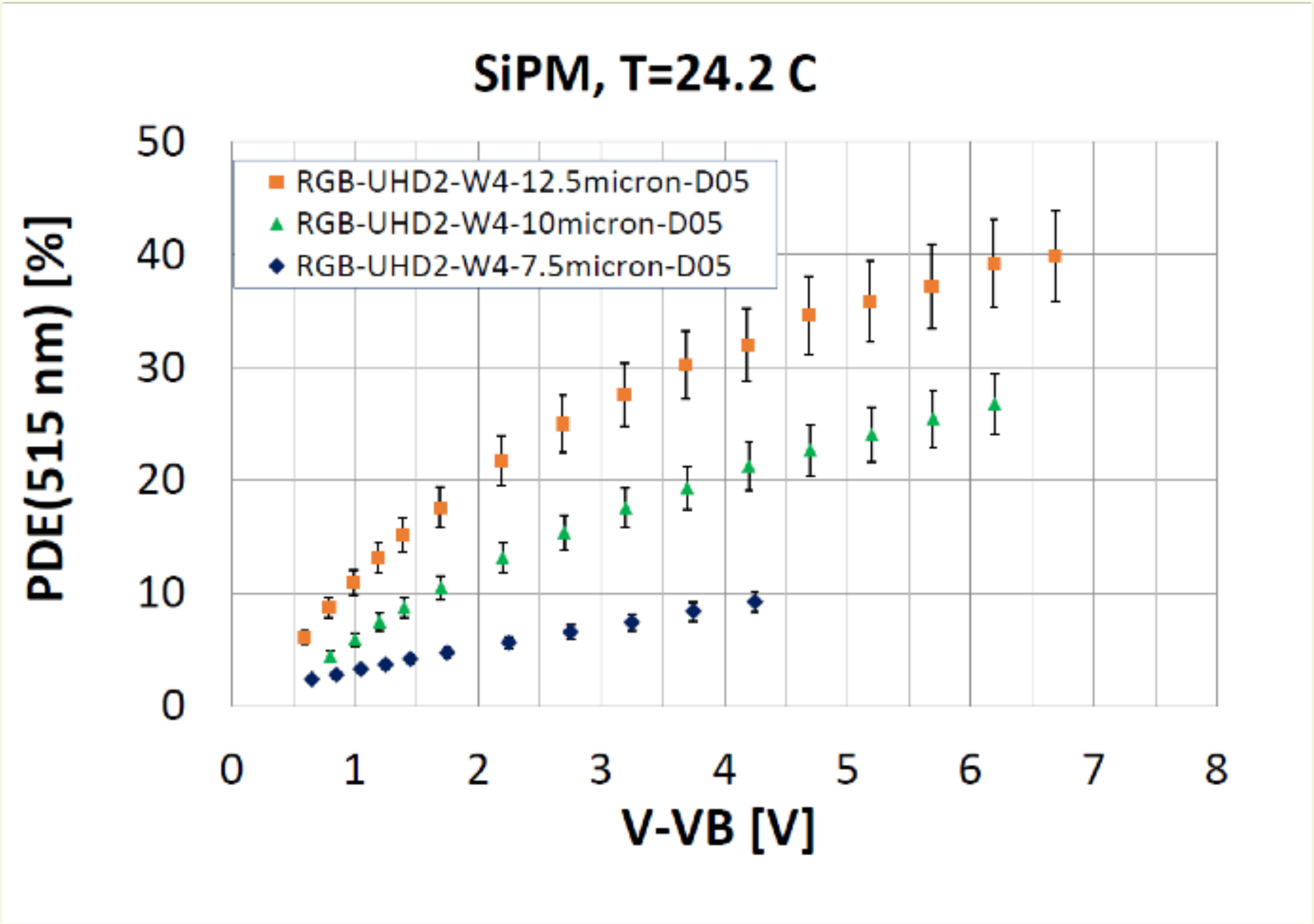
Cell size (um)	Equivalent square cell (um)	Cell density (cells/mm^2)	Fill Factor (L = 0.75 um)	Fill Factor (L = 1.25 um)
7.5	7	**20530**	**57.1%**	40.3%
10	9.3	11550	68.1%	54%
12.5	11.6	7400	74.5%	62.1%

L = 0.75 um

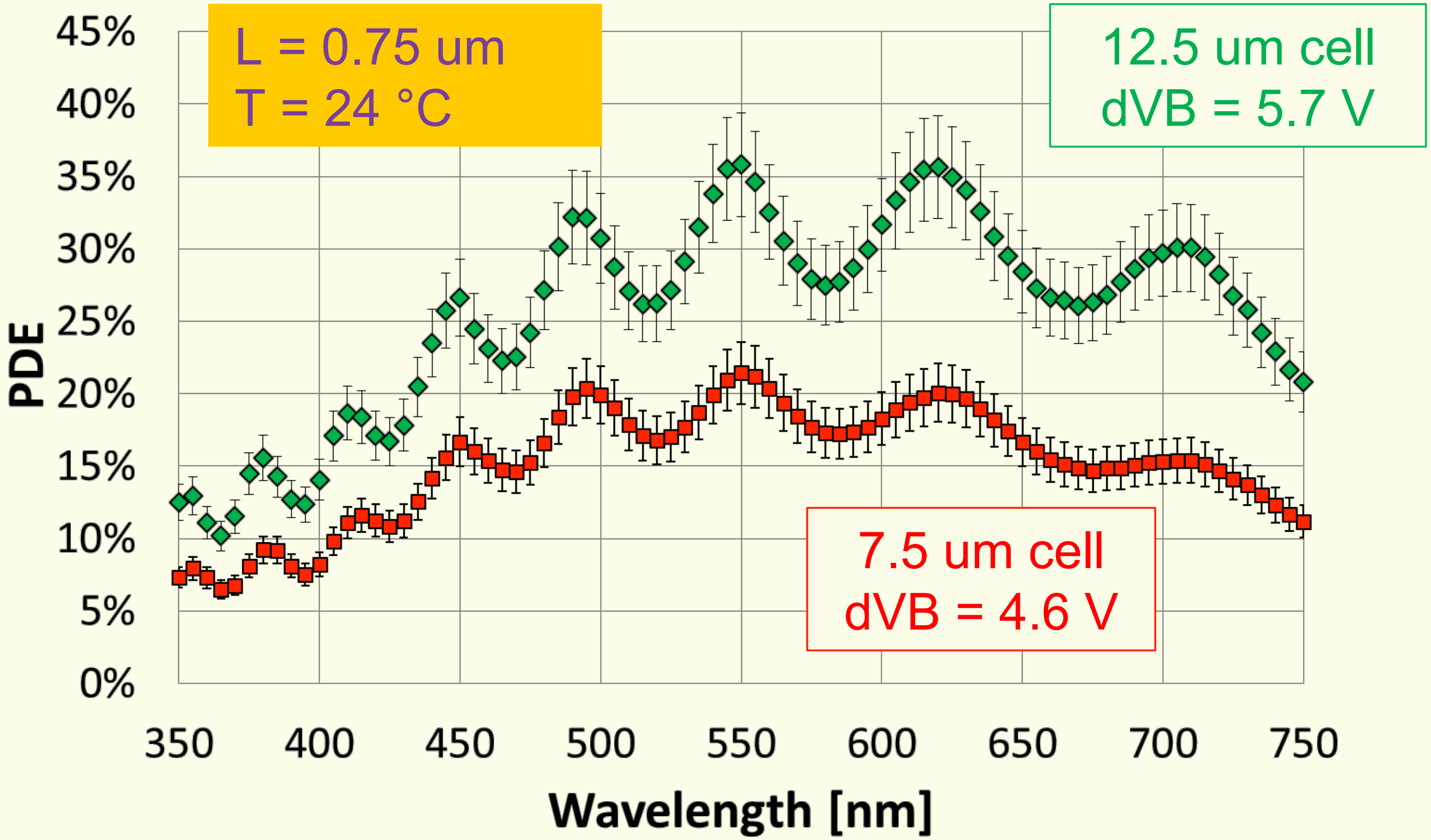


Layout of different microcells.

Cell size vs PDE

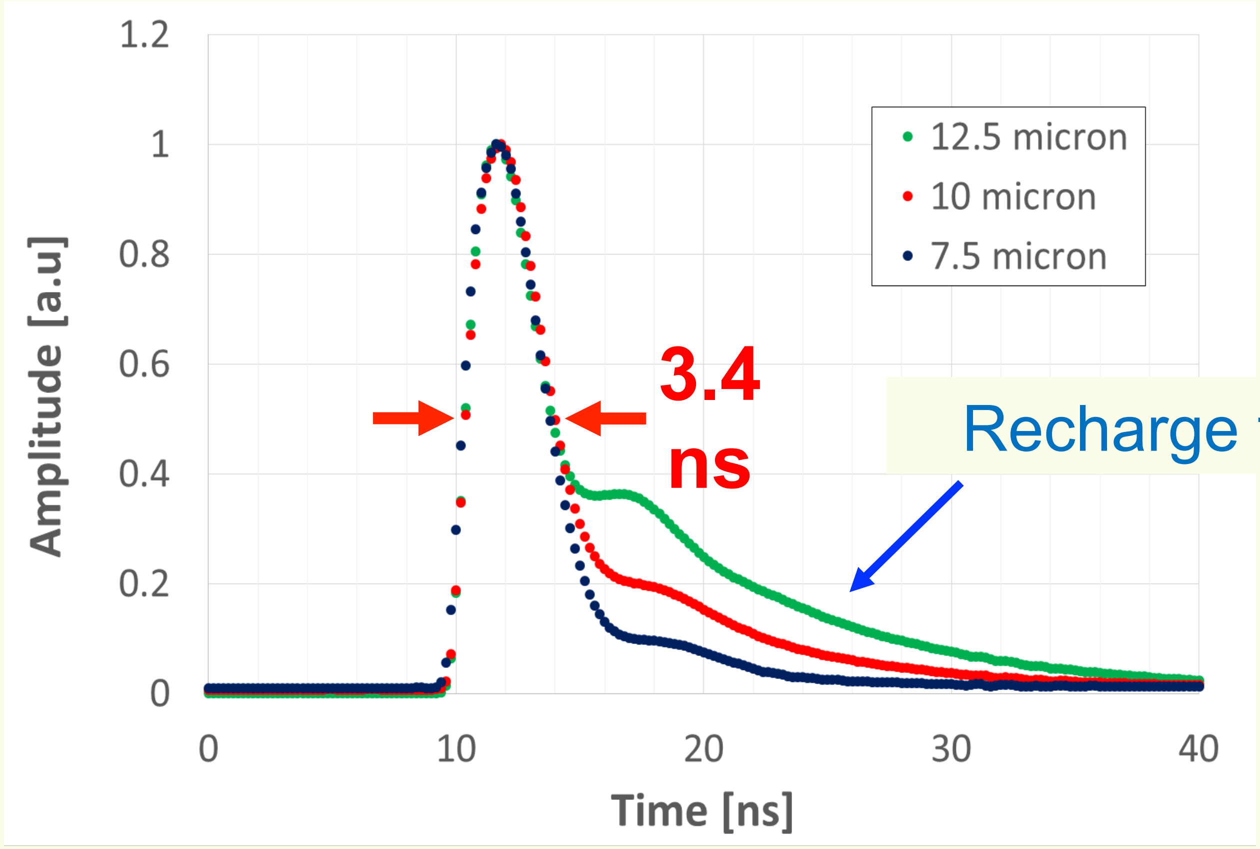


UHD SiPM spectral response



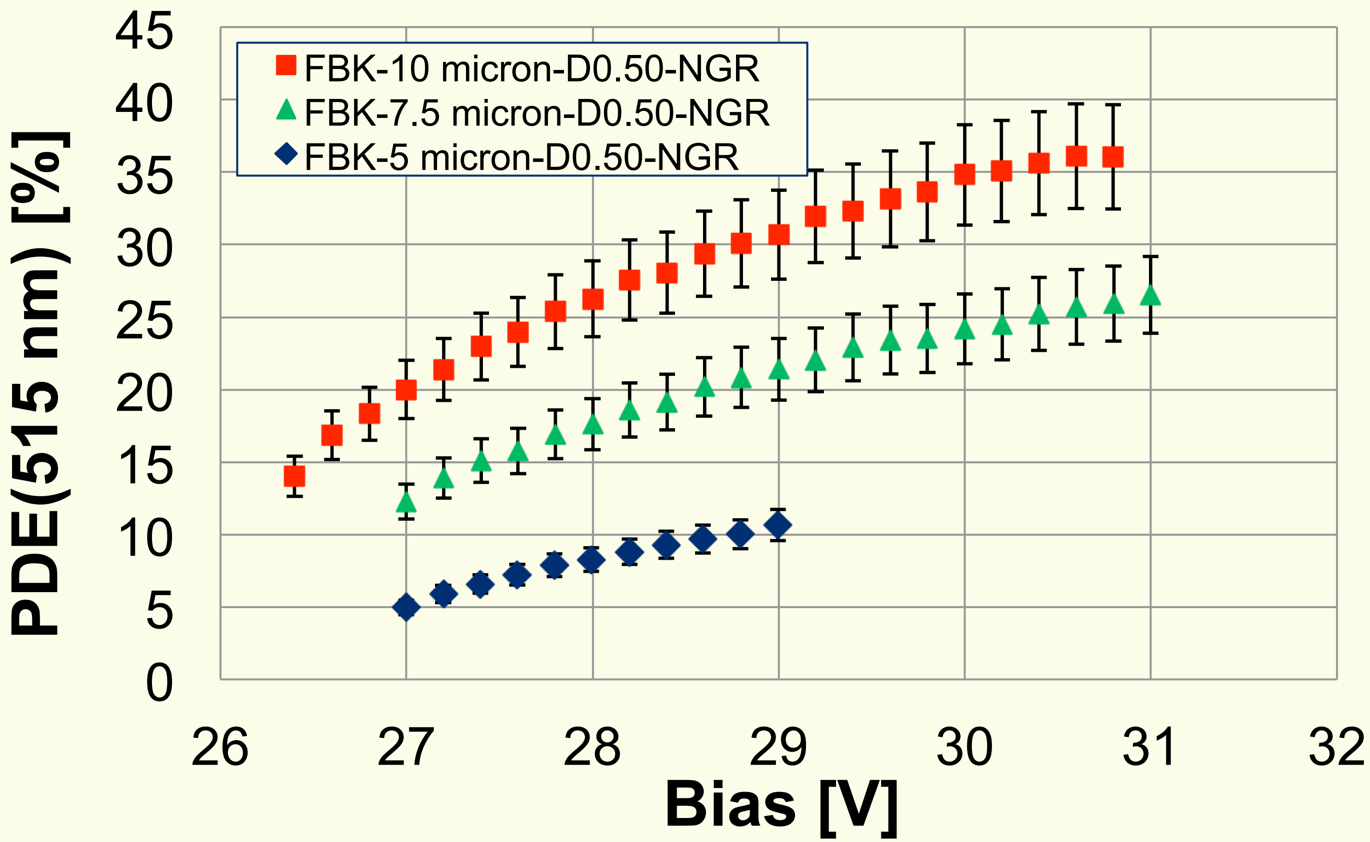
Average response to the laser pulse

500 MHz BW



UHD2: Much higher PDE with New Guard Ring

Optimized guard ring → higher PDE~25% for 7.5 um cell pitch SiPMs



Summary and future plans

Summary.

- Functionality of the UHD technology, with cells sizes of (less than 7.5 um, 10 um and 12.5 um) has been demonstrated.
- Very short recovery time constant: ~4 ns (7.5 and 10 um cells).
- Low gain: 30k / V (7.5 um cell), 43k / V (10 um) and 70k / V (12.5 um).
- High PDE, greater than 25% (7.5 um) and 40% (12.5 um).

Future plans.

- Optimization of guard ring structure to increase PDE and reduce gain of 5 um cell pitch SiPM
- Electric field engineering to reduce dark noise generation rate
- Radiation damage studies of different SiPM designs to understand and improve SiPM resistance to radiation
- Development of UV sensitive devices with small pixels

- Work supported in part by the National Science Foundation through the USCMS Upgrade and Operations Programs and the University of Notre Dame

Back-up: NIEL factor